

Importance of lifetime effects in breakup and suppression of complete fusion in reactions of weakly bound nuclei

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Background: Complete fusion cross sections in collisions of light, weakly bound nuclei and high Z targets show suppression of complete fusion at above-barrier energies. This has been interpreted as resulting from breakup of the weakly bound nucleus prior to reaching the fusion barrier, reducing the probability of complete charge capture. Below-barrier studies of reactions of ^9Be have found that breakup of ^8Be formed by neutron stripping dominates over direct breakup, and that transfer triggered breakup may account for the observed suppression of complete fusion.

Purpose: This paper investigates how the above conclusions are affected by lifetimes of the resonant states that are populated prior to breakup. If the mean life of a populated resonance (above the breakup threshold) is much longer than the fusion timescale, then its breakup (decay) cannot suppress complete fusion. For short-lived resonances, the situation is more complex. This work explicitly includes the mean life of the short-lived 2^+ resonance in ^8Be in classical dynamical model calculations to determine its effect on energy and angular correlations of the breakup fragments and on model predictions of suppression of cross sections for complete fusion at above-barrier energies.

Method: Previously performed coincidence measurements of breakup fragments produced in reactions of ^9Be with ^{144}Sm , ^{168}Er , ^{186}W , ^{196}Pt , ^{208}Pb and ^{209}Bi at energies below the barrier have been re-analysed using an improved efficiency determination of the BALiN detector array. Predictions of breakup observables and of complete and incomplete fusion at energies above the fusion barrier are then made using the classical dynamical simulation code PLATYPUS, modified to include the effect of lifetimes of resonant states.

Results: The agreement of the breakup observables is much improved when lifetime effects are included explicitly. Sensitivity to sub-zeptosecond lifetime is observed. The predicted suppression of complete fusion due to breakup is nearly independent of Z , and has an average value of $\sim 9\%$. This is below the experimentally determined fusion suppression which is typically $\sim 30\%$ in these systems.

Conclusions: Inclusion of resonance lifetimes is essential to correctly reproduce breakup observables. This results in a larger fraction of nuclei remaining intact at the fusion barrier radius, compared with calculations that do not explicitly include lifetime effects. The more realistic treatment of breakup followed in this work leads to the conclusion that the suppression of complete fusion cannot be fully explained by breakup prior to reaching the fusion barrier. Only one third of the observed fusion suppression can be attributed to the competing process of breakup. Other mechanisms that can suppress complete fusion must therefore be investigated. One of the possible candidates in cluster transfer that produces the same heavy target-like nuclei as those formed by incomplete fusion.

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I. INTRODUCTION

The causes of complete fusion suppression in above-barrier reactions with light, weakly bound nuclei is a key question in fusion dynamics. Fusion measurements of $^9\text{Be} + ^{208}\text{Pb}$, ^{209}Bi [1–4] and $^6,^7\text{Li} + ^{209}\text{Bi}$ [2, 5] show that above-barrier complete fusion cross sections (experimentally defined as capture of the full charge of the projectile) are reduced by $\sim 30\%$, both in comparison with those predicted by complete fusion models and with measurements for well-bound nuclei forming the same compound nucleus [2, 6]. Complete fusion suppression in reactions with ^9Be has been observed for a variety of targets in the range $39 \leq Z \leq 83$ [4, 7–10]. This suppression was initially suggested to result from direct breakup of

$^9\text{Be} \rightarrow \alpha + \alpha + n$ prior to reaching the fusion barrier [1]. It was conjectured that breakup reduces the probability of the full charge of the projectile-like nucleus being captured, thus suppressing complete fusion (CF), and increasing the incomplete fusion (ICF) cross-sections.

Experiments were undertaken to probe the extent of the role of breakup in complete fusion suppression. These experiments were performed at below-barrier energies to allow clearer investigation of breakup, as there is essentially no absorption of the charged fragments [11]. These investigations found that transfer followed by breakup contributes much more than direct breakup to the total breakup probability [12, 13]. In the case of ^9Be , breakup in interactions with ^{144}Sm , ^{168}Er , ^{186}W , ^{196}Pt , ^{208}Pb and ^{209}Bi is dominated by neutron stripping forming ^8Be which subsequently breaks up into $\alpha + \alpha$, rather than ^9Be undergoing direct breakup into $\alpha + \alpha + n$ or $^8\text{Be} + n$.

It was recognised early on [11] that very long-lived

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states, such as the 0^+ ground-state of ^8Be , which has a mean life of $\sim 10^{-16}$ s [14], results in breakup far from the target-like nucleus. It therefore cannot contribute to complete fusion suppression. At above-barrier energies, the ^8Be nucleus in its ground-state will pass inside the fusion barrier and be absorbed before decay can occur. However, population of broad resonances with much shorter mean lives will result in breakup close to the target-like nucleus.

The question then is: what is the quantitative contribution of near-target transfer-triggered breakup to the suppression of complete fusion? This was previously addressed by first obtaining breakup probabilities as a function of distance of closest approach (“breakup functions”) [12] at below-barrier energies. These breakup functions were then used as input to the classical dynamical model code PLATYPUS [15, 16], to predict complete and incomplete fusion cross-sections at above-barrier energies [12, 15] that agreed satisfactorily with experimental results [2, 4, 7, 10].

In PLATYPUS, the lifetimes of the states populated were not explicitly taken into account. However, locations of breakup and the lifetimes of states are intimately related: finite but small mean lives will change the positions at which breakup occurs along the trajectory of the nuclei. Indeed, recent work [17] has highlighted that the precise location of breakup relative to the target-like nucleus is critical to reaction outcomes, and further, that there exist experimental observables that can probe these effects.

In this work, we investigate quantitatively the effect of the lifetime of short-lived resonant states on breakup processes and the resultant incomplete fusion. Measurements of transfer reactions populating ^8Be can be completely explained by the population of ^8Be in its 0^+ , 2^+ , and at higher excitations, 4^+ states [18, 19]. In breakup following ^7Li collisions with ^{58}Ni , it has been shown that transfer populates the 0^+ and 2^+ states in ^8Be [17]. The 3.03 MeV 2^+ state of ^8Be has an on-resonance width of $\Gamma(E_R) = 1513 \pm 15$ keV, and thus a mean life of $\tau = \hbar/\Gamma(E_R) = 0.44 \times 10^{-21}$ s [14]. As such, breakup from this state will occur very close to the target-like nucleus. To determine the effect on complete fusion, it is then necessary to quantitatively understand whether such short mean lives carry a significant fraction of excited projectile-like nuclei inside the fusion barrier before breakup occurs, thus reducing the suppression of complete fusion due to breakup.

To address this question, this work presents a re-analysis of the extensive sub-barrier breakup measurements of Rafiei *et al.* [12], using a modified version of PLATYPUS which incorporates resonance lifetimes. The re-analysis of these experimental data is presented in Sec. II. An improved method has been used to better determine the coincidence detection efficiency of the detector array, discussed in Sec. III. As a result of these changes, a different efficiency correction for the detector geometry has resulted, which feeds back into the determination of

the breakup function – the probability of breakup along a trajectory with distance of closest approach R_{min} – given as input into PLATYPUS. Model sensitivities to breakup observables and the resultant modifications to PLATYPUS are discussed in Sec. IV. New below-barrier breakup functions are derived in Sec. V. The calculations of above-barrier fractions of incomplete fusion are presented in Sec. VI, and the consequences of these calculations for the role of breakup in the suppression of complete fusion is discussed in Sec. VII.

II. DATA ANALYSIS

Full experimental details for the data analysed here can be found in Ref. [12], and a brief summary is given here for completeness. Beams of ^9Be at below-barrier energies were delivered by the 14UD electrostatic accelerator at the Australian National University Heavy Ion Accelerator Facility onto isotopically enriched targets of ^{144}Sm , ^{168}Er , ^{186}W , ^{196}Pt , ^{208}Pb and ^{209}Bi . The breakup of ^9Be , whether direct or triggered by neutron stripping, results in two coincident α particles. The Breakup Array for Light Nuclei (BALiN) was used to detect these coincident fragments. The array is composed of four Double-sided Silicon Strip Detectors (DSSDs), each with 16 arcs and 8 sectors, resulting in 512 effective pixels over the array. Below-barrier ($E/V_B \sim 0.65 - 0.9$) measurements of coincident $\alpha - \alpha$ pairs were made, as reported in Ref. [12], with the goal of extracting breakup probabilities as a function of the distance of closest approach. In analyses such as these, the challenge is in separating coincident breakup events from all other reaction outcomes that result in coincident signals in a detector array. Genuine coincident breakup events were distinguished from spurious coincidence events (mainly resulting from random coincidences between scattered projectiles and electronic noise), by selecting the characteristic diagonal bands that appear when plotting the energy of one coincident particle (E_1) against the energy of the other (E_2) (see, for example, Fig. 3 of Ref. [12]). For completeness, in Appendix A we describe an improved method for removal of spurious coincidence events resulting from cross-talk or particles crossing an interstrip partition, which are not removed by E_1 - E_2 gating.

A. Distinguishing near-target and asymptotic breakup

After the removal of spurious events, the reconstructed spectra of reaction Q-value against relative energy of the two coincident breakup fragments, E_{rel} , for $^9\text{Be} + ^{144}\text{Sm}$, ^{168}Er , ^{186}W , ^{196}Pt , ^{208}Pb and ^{209}Bi at centre of mass energy $E_{c.m.}$ such that $\frac{E_{c.m.}}{V_B} \sim 0.9$ are shown in Fig. 1. Compared to previous results, at this stage in the re-analysis, the data differ mainly in the larger number of events from ^8Be ground-state decay, as noted in Ap-

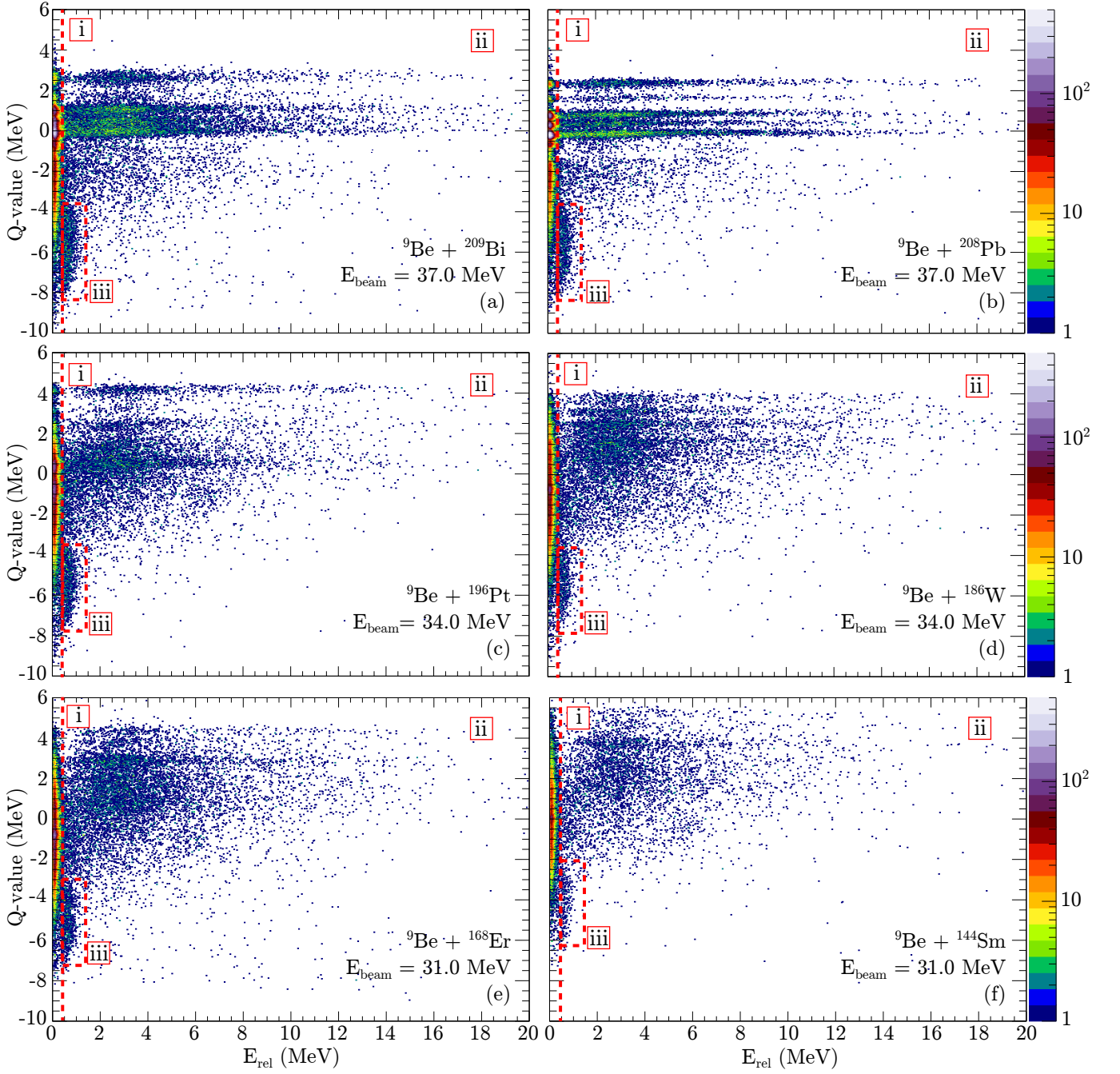


FIG. 1. (Colour online) Spectra of the reconstructed E_{rel} against Q -value for the reactions studied in this re-analysis. Measurements at centre-of mass energies of $E_{c.m.}/V_B \sim 0.9$ are shown. Events arising from the breakup of ^8Be from its 0^+ ground state, which includes contributions from direct ($^9\text{Be} \rightarrow ^8\text{Be}_{0^+} + n$) and transfer-triggered breakup are shown to the left of the vertical dashed line denoted region (i). Events from breakup of ^8Be from either the high excitation energy tail of the 0^+ state or the 2^+ , 4^+ states lie to the right of the line [region (ii)], excepting those marked by the dashed box, (iii), which contains direct breakup events from the decay of ^9Be from its $\frac{5}{2}^-$ state.

pendix A. The Q -values are determined by

$$Q = (E_1 + E_2 + E_{\text{recoil}}) - E_{\text{lab}}, \quad (1)$$

where E_i are the energies of each fragment, corrected for energy loss through the target, mylar foil, aluminium

layer and silicon dead-layer, E_{lab} is the beam energy after traversing half the target thickness, and E_{recoil} is the energy of the recoiling target-like nucleus, which is determined through momentum conservation. As discussed in Ref. [12], the distribution of Q -values reflects the exci-

tation of the target-like nucleus. The E_{rel} distribution is determined using the expression

$$E_{\text{rel}} = \frac{m_2 E_1 + m_1 E_2 - 2\sqrt{m_1 E_1 m_2 E_2} \cos \theta_{12}}{m_1 + m_2}, \quad (2)$$

where θ_{12} is the measured laboratory frame opening angle, given by

$$\cos \theta_{12} = \cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos(\phi_1 - \phi_2), \quad (3)$$

m_i and E_i are the mass and energy of each fragment, and (θ_i, ϕ_i) is the measured scattering angle and azimuthal angle of each signal in a coincidence event. The E_{rel} distribution reflects the excitation of the projectile-like nucleus, modified by post breakup Coulomb interactions of the fragments with the target-like nucleus. Events with small relative energy $E_{\text{rel}} \lesssim 180$ keV, labelled region (i), result from breakup of the ^8Be ground state with $E_{\text{rel}} = 92$ keV. The spread in measured E_{rel} up to 180 keV results from the angular size of the detector pixels [20]. This unbound state has a width $\Gamma = 5.57 \pm 0.25$ eV, and therefore mean life $\tau = 1.2 \times 10^{-16}$ s [14]. Due to this long mean life, breakup will occur asymptotically far from the target-like nucleus, such that the gradient of the Coulomb field accelerates the two fragments in essentially the same direction.

On the other hand, events with large E_{rel} , labelled as region (ii), is associated with breakup of ^8Be which results in high relative energy. One contributor to such events is breakup of ^8Be from its 2^+ resonant state. This state has a large width, $\Gamma = 1513 \pm 15$ keV, and thus a mean life 4.35×10^{-22} s [14]. ^8Be populated in this state will therefore break up close to the target-like nucleus, where fragment-target interactions significantly affect the trajectory of the breakup fragments. It is these events that may influence complete and incomplete fusion cross-sections at above-barrier energies.

Events resulting from direct breakup of ^9Be ($^9\text{Be}^* \rightarrow \alpha + \alpha + n$) from the 2.43 MeV $\frac{5}{2}^-$ state [14] are grouped in the region labelled (iii) in each panel. The spread in Q -values reflects the fact that the energy carried by the neutron is not captured by the BALiN array, resulting in an incorrect reconstruction of the Q -value of this breakup mode. Despite missing the neutron, the distribution is relatively sharply peaked in E_{rel} (~ 0.6 MeV) reflecting the long mean life of $\tau \sim 8.4 \times 10^{-19}$ s ($\Gamma = 0.78 \pm 0.13$ keV) of this state [14]. Breakup from this state will thus also occur far from the target-like nucleus, giving minimal differential acceleration of the α particles following breakup.

Independent of expectations based on the known mean lives of resonant states, deduced from their widths, it is possible to experimentally separate breakup close to the target nucleus from breakup (asymptotically) far away by examining the energy and angular correlations of the resulting fragments [17, 21]. When breakup occurs asymptotically, which is also associated with a well defined excitation energy E_x of the projectile-like nucleus, the laboratory opening angle between the two fragments, θ_{12} , and

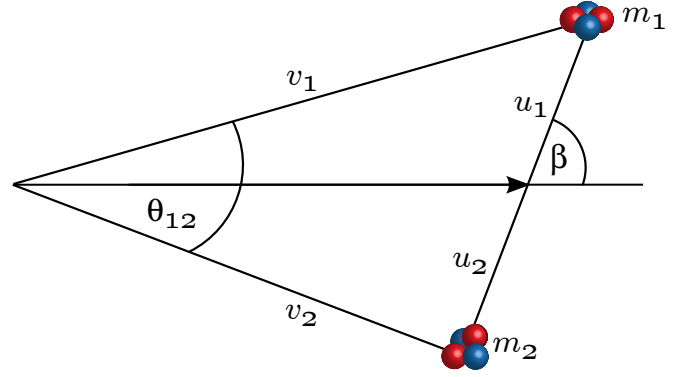


FIG. 2. (Color online) Diagram demonstrating the relationship between opening angle θ_{12} and the orientation of the relative momenta of the breakup fragments β . v_i is the laboratory velocity for each fragment with mass m_i , and is deduced from their measured energy E_i . u_i is the velocity of each fragment in their centre of mass frame, deduced from momentum conservation and their relative energy.

the orientation of the relative momentum of the breakup fragments, β , in their centre of mass frame are related. These quantities, θ_{12} and β , are shown in Fig. 2, which can be used to obtain the relationship:

$$\sin \beta = \frac{v_1 v_2 \sin \theta_{12}}{(v_2^2 u_1^2 + v_1^2 u_2^2 + 2u_1 u_2 v_1 v_2 \cos \theta_{12})^{1/2}}. \quad (4)$$

Here, v_i is the laboratory velocity for each fragment, deduced from their measured energy E_i , and u_i is the velocity of each fragment in their centre of mass frame, deduced from momentum conservation and their relative energy $E_{\text{rel}} = \frac{1}{2}\mu_{12}(u_1 + u_2)^2$, $\mu_{12} = \frac{m_1 m_2}{m_1 + m_2}$. The $\theta_{12} - \beta$ distributions, reconstructed from the measured data for $^9\text{Be} + ^{186}\text{W}$ at $E_{\text{beam}} = 37.0$ MeV are shown in Fig. 3 for $Q > -3$ MeV (panel a), where transfer-triggered breakup is dominant, and for $Q < -3$ MeV (panel b). The latter includes contributions from direct breakup, which are those shown in region (iii) of Fig. 1(d) for the same system at $E_{\text{beam}} = 34.0$ MeV. The lines overlaid on the data in Fig. 3 correspond to calculations using Eqn. (4) for E_x corresponding to breakup from (from left to right) ^8Be 0^+ , $E_x = 92$ keV, ^9Be $\frac{5}{2}^-$, $E_x = 600$ keV [region (iii) in Fig. 1], and ^8Be 2^+ , $E_x = 3.03$ MeV. As can be seen in the figure, bands with excellent correspondence to the calculations for the asymptotic breakup of ^8Be 0^+ and ^9Be $\frac{5}{2}^-$ are present in the experimental $\theta_{12} - \beta$ distribution, confirming the interpretation that these events correspond to breakup asymptotically far from the target-like nucleus. However, as can be seen in Fig. 3(a), the calculation assuming asymptotic breakup of ^8Be 2^+ does not match the data well. This can be explained as a result of breakup occurring close to the target-like nucleus. When this occurs, the initial kinetic energy of the fragments is small, and their energies are stored in the fragment-target potential. As a result, there

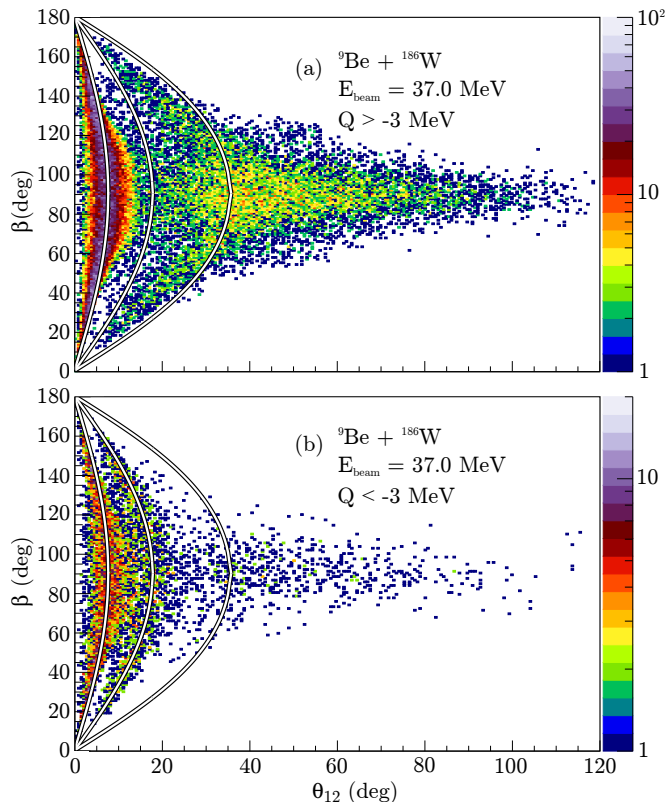


FIG. 3. (Colour online) Deduced experimental $\theta_{12} - \beta$ distribution for the breakup of ^8Be formed after neutron transfer from ^9Be in interactions with ^{186}W at $E_{\text{beam}} = 37$ MeV. Panel (a) shows $Q > -3$ MeV to highlight transfer-triggered breakup, and (b) shows events with $Q < -3$ MeV, where the direct $^9\text{Be } \frac{5}{2}^-$ curve is more clearly seen. Lines indicate $\theta_{12} - \beta$ curves calculated for the asymptotic breakup of (left to right) $^8\text{Be } 0^+$, $^9\text{Be } \frac{5}{2}^-$ and $^8\text{Be } 2^+$. Distributions that deviate from these curves are a result of breakup that occurs sufficiently close to the target-like nucleus to perturb the final trajectories of the breakup fragments. If particles fall into the same pixel of BALiN, they do not register as coincidence events, resulting in a reduced number of events observed near $\beta = 0^\circ$ and 180° .

is an increased probability for $E_1 \sim E_2$ and thus of deduced values of $\beta \sim 90^\circ$ for breakup into identical fragments [17]. Therefore, without making any assumption of the state that is populated, the concentration of events around $\beta \sim 90^\circ$, indicates breakup close to the target-nucleus. Thus it is these events that may influence complete fusion cross-sections. The extraction of breakup probabilities for these events is the subject of Sec. III and V.

B. Cross-section normalisation

In order to extract breakup probabilities, the array was partitioned into 5° bins covering laboratory angles from $\theta = 130^\circ$ to 165° . The yield of breakup events in each bin

must be normalised to the yield of Rutherford scattering. Elastic events for normalisation were extracted from a θ bin of the BALiN array from $124^\circ - 127^\circ$, where the elastic yield is pure Rutherford for deep sub-barrier measurements. At higher energies, the yield was corrected by up to 11%, determined from optical model calculations, described in Appendix B. Recent precision measurements of the spatial positioning of the BALiN detectors have resulted in slight changes in the location of the array relative to the beam axis. This has resulted a $9 \pm 1\%$ decrease in the number of elastic particles assigned to the $124^\circ - 127^\circ$ bin for each measurement compared to those reported in Ref. [12].

III. IMPROVED METHOD FOR COINCIDENCE EFFICIENCY DETERMINATION

In order to determine absolute breakup probabilities, the coincidence efficiency ϵ of BALiN had to be determined. In this work, a new two-step approach to efficiency determination was implemented with minimal reliance on simulated breakup distributions. The first step was to calculate the geometric coincidence efficiency of the BALiN array as a function of θ_{12} and breakup pseudo-angle $\theta_{s\text{Be}}$ (described below). A Monte-Carlo simulation was used to obtain these geometric coincidence efficiencies. PLATYPUS was used as the Monte-Carlo simulator, but the efficiencies derived in this step were model-independent. However, the geometric coincidence efficiencies did not account for the events that fall outside of the detector acceptance in $(\theta_{s\text{Be}}, \theta_{12})$. The second step in the efficiency determination was to simulate the total distribution of fragments to correct for those events with θ_{12} that fall outside the detector acceptance for each $\theta_{s\text{Be}}$. This correction was small – the events comprised $\sim 7\%$ of the total yield in the $\theta_{s\text{Be}}$ acceptance of the detector. These simulations were done using a version of PLATYPUS which incorporated the modifications discussed in Sec. IV. Full details of the efficiency determination is described in Appendix C, and a comparison of the efficiencies calculated in this work to those of Ref. [12] is presented in Appendix D.

The breakup pseudo-angle is also needed in order to extract breakup functions from coincidence data. When a reaction produces only one nucleus related to the lighter collision partner in the outgoing trajectory, the angular distribution and distance of closest approach of the projectile and target nuclei may be estimated from the measured scattering angle in a straightforward manner. In a breakup reaction producing pairs of particles which will have different angles θ and ϕ , an appropriate way to extract the breakup function is by use of $\theta_{s\text{Be}}$, which can be interpreted as the reconstructed scattering angle of the ^8Be had it not broken up. This is related to the deduced recoil angle of the target-like nucleus θ_{recoil} . The latter is already used to calculate the kinetic energy of the recoiling target-like nucleus and thus the Q -value

of the breakup reactions. θ_{recoil} is determined from the momenta of the measured breakup fragments using momentum conservation, and θ_{sBe} is given by

$$\tan \theta_{\text{sBe}} = \frac{\sin 2\theta_{\text{recoil}}}{M_p/M_t - \cos 2\theta_{\text{recoil}}}, \quad (5)$$

where M_p is the mass of the projectile-like nucleus and M_t the mass of the target-like nucleus.

IV. CLASSICAL TRAJECTORY SIMULATIONS

The ultimate aim of this work is to understand the contribution that transfer triggered breakup makes to the suppression of complete fusion at energies above the barrier. By making below-barrier measurements of no-capture breakup probabilities and relating these probabilities to above-barrier CF and ICF cross-sections, it is possible to determine the contributions of breakup to suppression of CF, and to cross sections for ICF products. However, to achieve this, a reliable simulation of post-breakup trajectories of the fragments is required. This is for two reasons: firstly, to extract the below-barrier near-target breakup probabilities from experimental results, and secondly, to take these experimentally determined breakup probabilities and make predictions of CF and ICF at above-barrier energies.

As no fully quantum mechanical model of transfer induced breakup exists yet, classical simulations have been performed. Clearly, it is important that a classical model captures the key physics of the breakup processes. Namely, (a) the locations of the transfer reactions, (b) the properties of the intermediate nucleus populated after transfer, and (c) the subsequent decay and post-breakup acceleration of the fragments. The acceleration of the fragments after breakup has the capacity to change their relative energy, and is the classical analogue of continuum-continuum couplings in quantum mechanical models. The classical dynamical breakup code PLATYPUS [15, 16], with modifications described below, provides an appropriate platform for these calculations. PLATYPUS is a three-body classical trajectory model with stochastic breakup that enables calculations of breakup observables as well as incomplete and complete fusion cross-sections. It considers a target and a weakly-bound pseudo-projectile (here, ^8Be) that initially follow Rutherford trajectories. Breakup probabilities and locations are stochastically sampled from an experimentally determined breakup function $P(R_{\text{min}})$. At the point of breakup, the properties of the fragments (excitation energy E_x , separation, orientation) are stochastically sampled before propagating in the fragment-fragment and fragment-target fields. Several significant modifications to PLATYPUS have been made to more accurately capture the details of breakup dynamics, as described below.

A. Incorporating excitation energies and lifetimes of resonant states of the projectile-like nucleus

In order to include the known low-energy structure of ^8Be , modifications to PLATYPUS were made to model the resonant states in ^8Be . The energy and angular distribution of breakup fragments produced after the decay of a projectile-like nucleus populated in transfer reactions depends critically on (i) the excitation of the projectile-like nucleus that breaks up, and (ii) the location of breakup with respect to the target-like nucleus, which is in turn sensitive to the lifetime of the projectile-like nucleus after the point of transfer. In the previous versions of PLATYPUS, the excitation of the projectile-like nucleus was given as a range from E_{min} to E_{max} with either a flat or exponentially decreasing distribution [16]. Although lifetimes were not treated explicitly, breakup fragments would take some time to propagate from their assumed initial Gaussian distribution of separations to beyond their mutual barrier radius [15]. This effective lifetime is sensitive to the fragment-fragment potential.

As will be demonstrated below, the population of ^8Be in the reactions studied in this work can be well described as a combination of 0^+ ground-state and first excited 2^+ state. Thus, the simulated excitation energy and lifetime distributions of ^8Be should correspond to the width of these states. Modifications to PLATYPUS were made such that excitation energies sampled from realistic distributions of excitation energy have a corresponding mean life associated with each excitation energy. The excitation energy probability distributions were calculated from the one-state, one-channel limit of R-matrix theory [18, 19]. The corresponding mean life was estimated using $\tau(E_x) = \hbar/\Gamma_\ell(E_x)$, where $\Gamma_\ell(E_x)$ is the energy-dependant resonance width. This has been recently described in Ref. [22], where excitation energy probability distributions were calculated for $^6,7\text{Li}$. Shown in Fig. 4 are the resulting excitation energy probability distributions (a) and excitation energy dependent mean lives (b) for the ^8Be 0^+ and 2^+ states used in the PLATYPUS calculations in this work.

Including these probability distributions of excitation energy and associated mean-life, the distribution of decay (breakup) times of short-lived resonance states are now modelled explicitly in PLATYPUS. The first step is randomly choosing a “transfer radius”, R_{Tr} , according to the breakup function as originally done. Then a classically allowed excitation energy E_x (with corresponding mean life τ) is chosen from the distribution of excitation energies as shown in Fig. 4. The projectile then propagates along its trajectory for some time t , sampled from the exponential distribution of times expected from the mean life, $e^{-t/\tau}$, before breaking up into two fragments with relative energy corresponding to E_x . The fragments are initially placed at a separation radius corresponding to the peak of their mutual barrier. Breakup is thus defined to occur when the two fragments pass their mutual barrier. Crucially, ^8Be produced by transfer before the

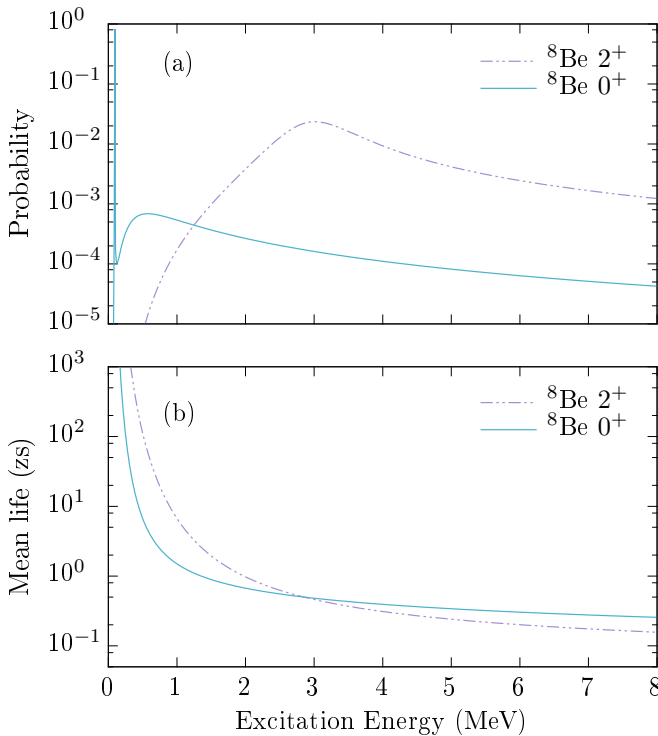


FIG. 4. (Colour online) Excitation energy probability distribution (a) and excitation energy dependant mean life (b) for 0^+ (solid line) and 2^+ (dashed line) states in ^8Be used as input in the modified version of PLATYPUS that explicitly takes into account resonance excitation energies and lifetimes.

distance of closest approach may pass the turning point and begin to recede from the target before breaking up.

This explicit handling of excitation energies and mean lives gives a more physically realistic (though still phenomenological) distribution of (i) breakup fragment energy and (ii) the time taken between transfer and breakup, and thus positions along the trajectories. The latter modification in particular removes sensitivity to the fragment-fragment potential. In addition, these modifications allow long-lived states, such as the ^8Be ground state, to be simulated with PLATYPUS rather than requiring an additional simulation with a different code [12]. Further, requiring that the distribution of excitation energies used in PLATYPUS be determined by the known resonance properties of ^8Be removes this quantity as a parameter in the model and, as discussed in Sec. VI, has a significant effect on CF and ICF predictions.

B. Incorporating effects of excitation of target-like nuclei

As can be seen by the spread of Q-values in Fig. 1, the target-like nucleus is populated with a large range of excitations (up to ~ 8 MeV) in these reactions. Trivially, as the excitation energy of the target-like nucleus increases,

the energy available for the excitation of the projectile-like nucleus decreases. This results in a decrease in E_{rel} (as can also be seen in Fig. 1), and thus a decrease in average opening angle θ_{12} . Therefore, the fidelity of the reproduction of experimental results in PLATYPUS is also dependent on the distribution of target-like excitations.

PLATYPUS, being a classical model, has radii around the classical turning point where transfer is classically forbidden due to energy conservation. The size of this region depends on the beam energy, angular momentum and the excitations of the projectile-like and target-like nuclei. The latter was not incorporated in the original version of PLATYPUS, which was thus modified to include the excitation energy distribution of the target-like nucleus, obtained from the experimentally determined Q-value distribution. As a result, the PLATYPUS simulation now reflects both the excited states of the target-like nucleus and the probability of populating those states in the neutron transfer reactions studied in this work. To model the excitation energy, at R_{Tr} an equivalent amount of kinetic energy is deducted from the projectile-like nucleus such that the direction of the relative velocity of the system is maintained.

C. Modifications to the local breakup function

The aim of these below-barrier measurements of breakup is to determine the breakup probabilities P as a function of R_{min} , the distance of closest approach on a Coulomb trajectory. The experimental data were fitted with the functional form

$$P(R_{\text{min}}) = e^{\mu R_{\text{min}} + \nu}, \quad (6)$$

where μ and ν are the (logarithmic) slope and intercept of the function, respectively. This function is interpreted as the integral of the local reaction probability $\mathcal{P}(R)$ along the classical orbit of the projectile,

$$P(R_{\text{min}}) = 2 \int_{R_{\text{min}}}^{\infty} \mathcal{P}(R) dR. \quad (7)$$

$\mathcal{P}(R)$ is a function of the projectile-target separation R , and $\mathcal{P}(R)dR$ gives the reaction probability between R and $R + dR$. The factor of two reflects the initial assumption that taking breakup to be instantaneous, it can occur with equal probability on the ingoing and outgoing trajectories. With the incorporation of resonance lifetimes, the local probability must now be interpreted as that for the trigger event for breakup, in this case transfer. At above-barrier energies, when using PLATYPUS to estimate σ_{ICF} , the distance of closest approach is inside the barrier radius, thus only the transfer probabilities on the ingoing trajectory should be included. This change by a factor of two has been taken into account in the modified PLATYPUS calculations of σ_{ICF} , resulting in a decrease in contributions to σ_{ICF} from trajectories

with angles within the grazing angle by approximately a factor of two.

The distribution of transfer positions along the projectile-target trajectory has also been modified. In the original PLATYPUS, when determining the probability along the trajectory it is assumed that since

$$2 \int_{R_{min}}^{\infty} \mathcal{P}(R) dR = e^{\mu R_{min} + \nu}, \quad (8)$$

the local probability must then have the form [15]:

$$\mathcal{P}(R) \propto e^{\mu R}. \quad (9)$$

However, this neglects the fact that interacting nuclei spend more time near the distance of closest approach than at other distances. As a result $dP(R_{min})/dt$ goes to zero at the point of closest approach, as illustrated in Appendix E for a classical Coulomb trajectory.

Instead, we assign each time step on a particular projectile trajectory a relative probability assuming a local (transfer) probability $\tilde{\mathcal{P}}(t) \propto e^{\mu R(t)}$ and normalise the full trajectory such that

$$P(R_{min}) = \int_{-\infty}^{\infty} \tilde{\mathcal{P}}(t) dt. \quad (10)$$

The local probability is then peaked at the distance of closest approach, which is physically more reasonable.

D. Comparison with experimental data

The accuracy of the PLATYPUS simulations was assessed by comparing them with the experimentally measured $\theta_{12} - \beta$ distributions. The $\theta_{12} - \beta$ distributions are a good test as they are sensitive to the effect of fragment-target interactions, and therefore to the position and energetics of breakup [17]. The experimental $\theta_{12} - \beta$ distribution for the breakup of ${}^8\text{Be}$ formed following neutron transfer in collisions of ${}^9\text{Be}$ with ${}^{209}\text{Bi}$ is shown in Fig 5(a). It is compared with modified and unmodified PLATYPUS simulations in Fig. 5(b) and (c), respectively. As the original PLATYPUS does not simulate long-lived states, the 0^+ state seen in the intense purple band at small θ_{12} in Fig. 5(a) has not been included. In the modified PLATYPUS simulation, both 0^+ and 2^+ resonances have been simulated, and the distributions are combined to produce the same ratio of breakup events that populate the $E_{\text{rel}} = 92$ keV 0^+ peak to the total number of events as seen in the experimental data.

As discussed in Sec. II, the effect of fragment-target Coulomb interactions results in deviations in the $\theta_{12} - \beta$ distribution from that expected for asymptotic breakup (calculated using Eqn. 4). The modified version of PLATYPUS well reproduces the 0^+ peak, and reproduces the high θ_{12} component better than the unmodified model (in particular events below the diagonal red dashed line, which is drawn to guide the eye). However, the simulation contains a higher intensity of events with $\theta_{12} \gtrsim 60^\circ$

and $\beta \sim 90^\circ$. This means that too many breakup events result in coincident fragments with similar energies and large opening angles. This discrepancy could be ameliorated by considering the effect of the projectile-target potential in producing a preferential orientation for ${}^8\text{Be}$ relative to the target, as has been previously explored for the direct breakup of ${}^7\text{Li}$ [23]. However, without a satisfactory method for reliably parameterising orientation effects, they are neglected, and all breakup is assumed to occur isotropically in the rest frame of ${}^8\text{Be}$. Nevertheless, these simulations demonstrate that the population of ${}^8\text{Be}$ in the reactions studied in this work can be reasonably well described as a combination of 0^+ ground-state and 2^+ first excited state. Further, the modifications to (i) better model the projectile-like nucleus in resonant states with explicitly included mean lives, (ii) model reactions that result in excitation of the target-like nucleus, and (iii) better distribute the transfer probability along the projectile-target trajectory provides a more physically realistic, though still phenomenological, model of breakup following transfer.

V. NEAR-TARGET BREAKUP PROBABILITIES

The breakup probability is defined for each $\theta_{s\text{Be}} \sim 5^\circ$ bin as the ratio between the breakup cross-section, determined from the yield of breakup fragments with the reconstructed angle of the unbroken projectile falling in $\theta_{s\text{Be}}$, and the Rutherford scattering cross-section for each $\theta_{s\text{Be}}$ bin,

$$P(\theta_{s\text{Be}}) = \frac{(\frac{d\sigma}{d\Omega})_{\text{BU}}(\theta_{s\text{Be}})}{(\frac{d\sigma}{d\Omega})_{\text{Ruth}}(\theta_{s\text{Be}})}. \quad (11)$$

The breakup pseudo-angle maps to a distance of closest approach of the target and unbroken projectile R_{min} , neglecting the nuclear potential at these sub-barrier energies, according to

$$R_{\text{min}} = \frac{Z_1 Z_2 e^2}{2E_{c.m.}} \left(1 + \frac{1}{\sin \frac{\theta_{s\text{Be}}}{2}} \right). \quad (12)$$

This definition of R_{min} implicitly assumes that the reconstructed scattering angle of the unbroken projectile-like nucleus is close to the Rutherford angle of the incoming projectile, that is, $\theta_{s\text{Be}} \approx \theta_{\text{Rutherford}}$. This assumption can be tested using PLATYPUS simulations. Shown in Fig. 6 is the Rutherford scattering angle of the pseudo-projectile derived from the incident trajectory, θ_{Ruth} , plotted against the reconstructed breakup pseudo-angle, for ${}^8\text{Be}_{2+} + {}^{207}\text{Pb} \rightarrow \alpha + \alpha$ at $E_{\text{beam}} = 34.0$ MeV. In the determination of the breakup functions, discussed in Sec. V, these deviations were treated as a correction to $\theta_{s\text{Be}}$, and for each $\theta_{s\text{Be}}$ bin, the average discrepancy between the Rutherford and reconstructed angles was subtracted from $\theta_{s\text{Be}}$. This correction was larger for breakup that

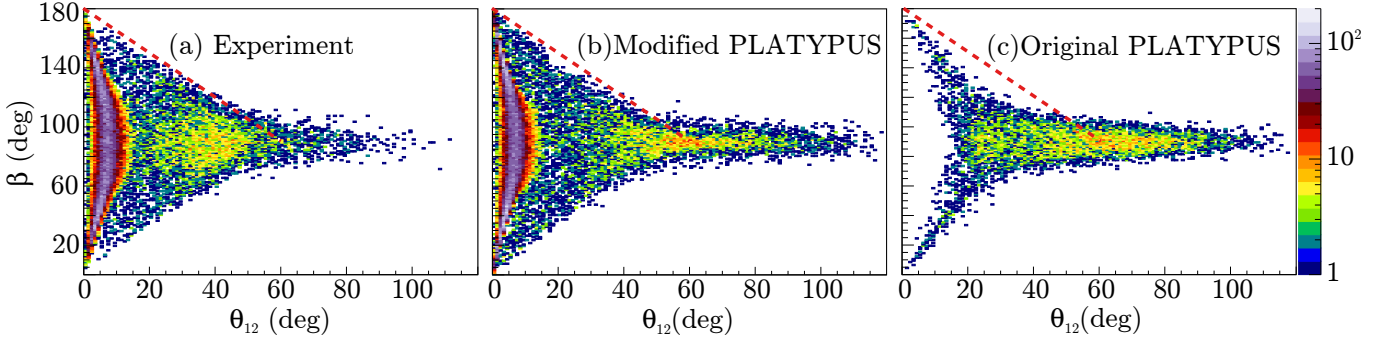


FIG. 5. (Colour online) (a) Measured $\theta_{12}-\beta$ distribution for the breakup of ${}^8\text{Be}$ formed following neutron transfer in interactions of ${}^9\text{Be}$ with ${}^{209}\text{Bi}$ at $E_{\text{beam}} = 34.0$ MeV. (b) The corresponding modified PLATYPUS simulation, which includes contribution from ${}^8\text{Be}$ 0^+ and 2^+ resonances. (c) The corresponding unmodified PLATYPUS simulation, with $0.95 \leq E_x \leq 4$ MeV, approximating the ${}^8\text{Be}$ 2^+ resonance only. The red diagonal line provides a reference to quantify the differences between the observables for the 2^+ resonance.

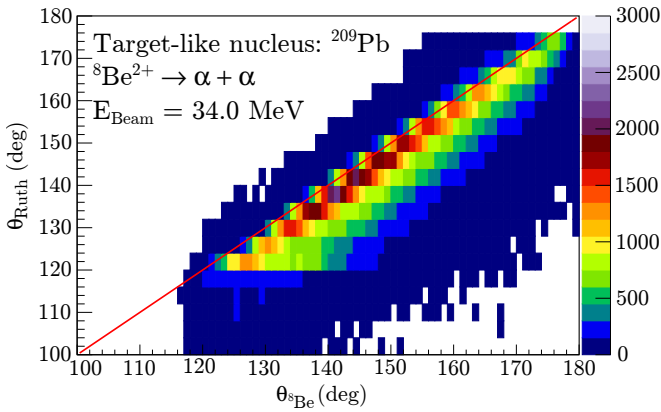


FIG. 6. (Colour online) PLATYPUS simulation for ${}^8\text{Be}_{2^+} + {}^{209}\text{Pb} \rightarrow \alpha + \alpha + {}^{209}\text{Pb}$ at $E_{\text{beam}} = 34.0$ MeV, for events that are captured by BALiN, demonstrating the relatively small difference between the Rutherford scattering angle of the ${}^8\text{Be}$ pseudo-projectile θ_{Ruth} and the angle $\theta_{s\text{Be}}$ that is reconstructed from the captured α particles.

occurs close to the target-like nucleus, and was Z dependent, varying from $\sim 1^\circ$ for ${}^9\text{Be} + {}^{144}\text{Sm}$, to $\sim 6^\circ$ for ${}^9\text{Be} + {}^{209}\text{Bi}$. As such, these discrepancies are likely due to trajectories that are perturbed by proximity to the high Z target-like nucleus.

With the corrected angle $\theta_{s\text{Be}}$ transformed to R_{min} , breakup functions may be determined experimentally from the ratio of efficiency corrected breakup yield to the elastic yield in each $\theta_{s\text{Be}}$ bin:

$$P(\theta_{s\text{Be}}) = \frac{N_{\text{BU}}(\theta_{s\text{Be}})}{N_{\text{Ruth}}(\theta_{\text{Ruth}})}. \quad (13)$$

Here $N_{\text{BU}}(\theta_{s\text{Be}})$ is the yield of near-target breakup events corrected for efficiency $\epsilon(\theta_{12}, \theta_{s\text{Be}})$, and $N_{\text{Ruth}}(\theta_{\text{Ruth}})$ the calculated Rutherford yield in a given θ_{Ruth} bin. Details of the determination of $N_{\text{Ruth}}(\theta_{\text{Ruth}})$ are given in Appendix B.

The resulting probabilities of near-target breakup are shown in Fig. 7(a). Each group of points in R_{min} represent measurements in 5° $\theta_{s\text{Be}}$ bins with different E_{beam} . A least-squares fit using Eqn. 6 to the experimental data was performed for each system, indicated by the solid lines in Fig. 7(a). These breakup functions provide a useful comparison to previous work. We also present an alternative parameterisation of the breakup function. A perhaps more intuitive way to parameterise breakup probabilities is as a function of the distance of closest approach relative to the average barrier radius R_{B} , in the form of Eqn. 4 of Ref. [24], such that

$$P_{\text{BU}} = P(R_{\text{B}})e^{\mu(R_{\text{min}} - R_{\text{B}})}, \quad (14)$$

where $P(R_{\text{B}})$ is the probability of breakup along a trajectory that reaches a distance of closest approach R_{B} , and μ the same slope parameter as in Eqn. 6. A detailed discussion of the physical significance of these parameters can be found in Ref. [24]. R_{B} was parameterised as $R_{\text{B}} = 1.44(A_T^{1/3} + A_P^{1/3})$, which reproduced the R_{B} of the calculated São Paulo potentials between the ${}^8\text{Be}$ and the target-like nucleus within 0.1 fm. Where the target nucleus is deformed, as is the case for ${}^{168}\text{Er}$ and ${}^{186}\text{W}$, the breakup function is an average over all orientations. The resulting breakup probabilities are shown in Fig. 7(b). From this, it is apparent that the dependence of breakup probability on the targets studied in this work is fairly small. Instead, near-target breakup is dominantly driven by how close the trajectory comes to R_{B} . This agrees with what was found in Ref. [12].

The fitted breakup slope parameters using both parameterisations are given in Table I. The reported uncertainties σ in the parameters come from each least-squares fit. The parameters μ and $P(R_{\text{B}})$ of the breakup functions are shown as a function of Z_T in Fig. 8. Unlike those found in Ref. [12], there is a fairly weak Z_T dependence on the fitted μ – a line of best fit yields $\mu = 0.005Z_T - 1.272$. There is also a trend of increasing $P(R_{\text{B}})$ with decreasing Z_T . This is correlated with

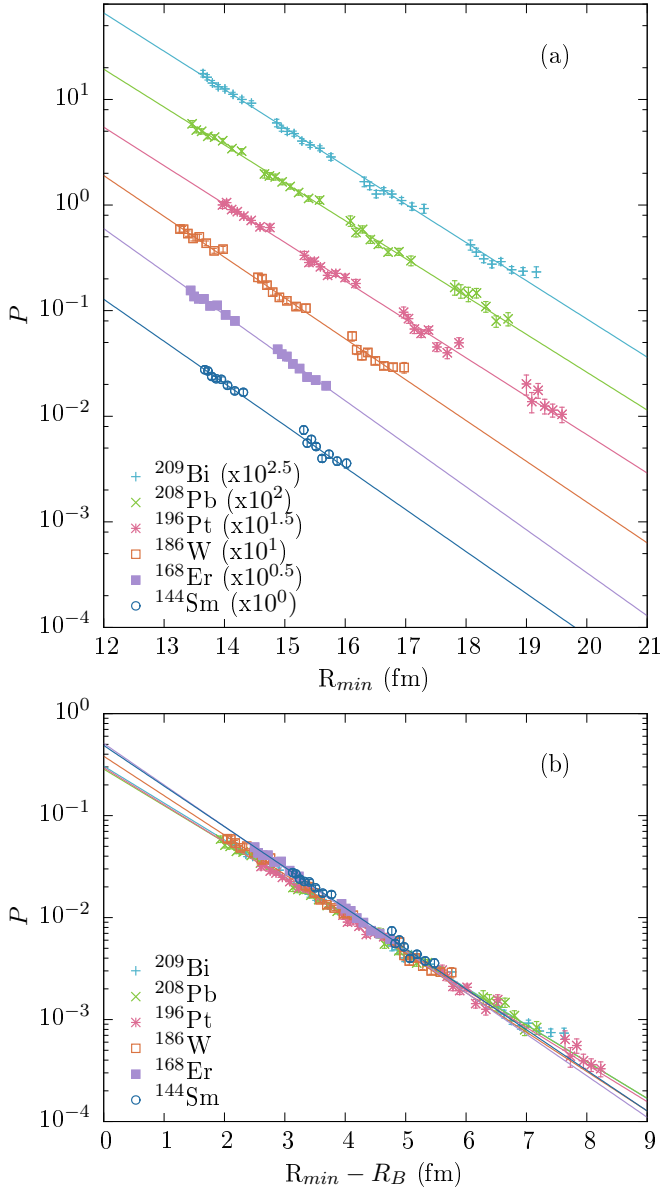


FIG. 7. (Colour online) Measured near-target (region *ii* of Fig. 1) breakup probabilities for the breakup of ^8Be formed following neutron transfer in reactions of ^9Be with ^{144}Sm , ^{168}Er , ^{186}W , ^{196}Pt , ^{208}Pb and ^{209}Bi at energies below the barrier (a) as a function of the separation of the centres of the nuclei, where probability values have been offset for clarity, as indicated in the legend, and (b) as a function of distance from the projectile-target barrier. Lines represent least-square fits with Eqn. 6. Errors in P are statistical, and for the most part, are smaller than the symbol size.

the trend of increasing ground-state neutron stripping Q -value with decreasing Z_T , as well as the number of states available for population near the the optimum Q -value of 0 MeV. It would be interesting to see how these trends evolve as Z_T decreases.

While the breakup functions derived in this work are

TABLE I. Near-target breakup function parameters determined through least-squares fits to the experimental data shown in Fig. 7 for the breakup of ^8Be formed after neutron transfer in reactions of ^9Be with ^{144}Sm , ^{168}Er , ^{186}W , ^{196}Pt , ^{208}Pb and ^{209}Bi .

	^{144}Sm	^{168}Er	^{186}W	^{196}Pt	^{208}Pb	^{209}Bi
μ (fm^{-1})	-0.92	-0.94	-0.89	-0.84	-0.83	-0.83
σ_μ (fm^{-1})	0.02	0.02	0.01	0.01	0.01	0.01
ν	9.0	9.6	9.0	8.3	8.3	8.4
σ_ν	0.3	0.3	0.2	0.2	0.2	0.1
$P(R_B)$	0.54	0.56	0.42	0.32	0.31	0.33
$\sigma_{P(R_B)}$	0.05	0.03	0.02	0.02	0.01	0.01

comparable to those found by Rafiei *et al.* [12], there is an average increase in the probability of breakup by a factor of 1.14 ± 0.09 at $R_{min} - R_B = 4$ fm. These differences result from the combined effects of several factors that have been discussed above, but are summarised here: (i) the Rutherford scattering yield in the normalisation bin for every measurement is a factor of 0.921 ± 0.009 lower due to slight refinement in the actual position of the BALiN array, (ii) the coincidence efficiency of these $\alpha - \alpha$ pairs calculated using PLATYPUS with respect to θ_{12} is different to that deduced in the previous work, and has a different Z_T and E_{beam} dependence, and (iii) correcting for coincidence efficiency produces an efficiency corrected yield over all azimuthal angles, and the calculation of the Rutherford yield must reflect this, as discussed in Appendix B. As seen in Fig. 8, the slope, μ , of the breakup function becomes shallower with increasing Z_T . The difference in average slope from the previous work is primarily driven by the two-dimensional coincidence efficiency correction used in this work. The improvements to PLATYPUS and to the efficiency determinations allow reliable cross-sections to be determined, which could be analysed using available semi-classical methods [25, 26]. With these new breakup functions, the next step is then to determine the impact of breakup on fusion suppression with the modified PLATYPUS model.

VI. ABOVE-BARRIER INCOMPLETE FUSION CROSS-SECTIONS

There have been two major approaches towards characterising fusion suppression in collisions with weakly bound nuclei. The first is through comparing measured above-barrier complete fusion cross sections to coupled-channels predictions of fusion cross-sections $\sigma_{CF}^{\text{expt.}}/\sigma_{\text{fus}}^{\text{calc.}}$ (e.g. [1, 2, 7–9]). This approach relies on accurate determination of the average barrier energy [2] and is somewhat model dependant [27]. The second approach equates fusion suppression to the fraction of incomplete fusion to total fusion $F_{\text{ICF}} = \frac{\sigma_{\text{ICF}}}{\sigma_{\text{ICF}} + \sigma_{\text{CF}}}$. Incomplete fusion is defined experimentally as capture of only part

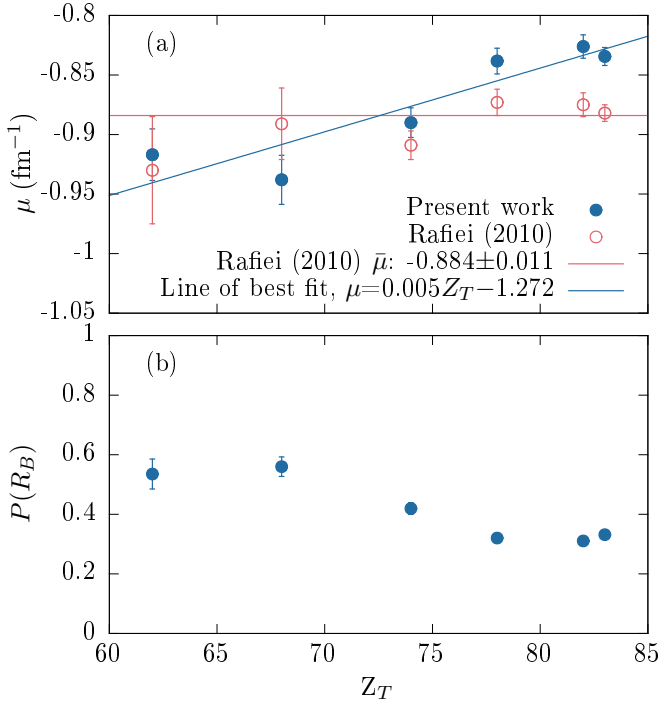


FIG. 8. (Colour online) (a) Filled circles: Slope parameters μ (fm^{-1}) derived from least-squares fits to the experimental data shown in Fig. 7(b), fit with $P_{\text{BU}} = P(R_B)e^{\mu(R_{\text{min}} - R_B)}$, shown as a function of target, Z_T . There is a slight Z_T dependence on the slope, indicated by the line of best fit $\mu = 0.005Z_T - 1.272$. Open circles show results from Ref. [12], which have mean slope $\bar{\mu} = -0.884 \pm 0.011$ (red line). The reasons for the discrepancies between the present and previous work are discussed in the text. (b) Corresponding $P(R_B)$ values derived from least-squares fits to the experimental data shown in Fig. 7(b), using Eqn. 14.

of the charge of the projectile. This approach is justified by measurements which find similar values for $(1 - \sigma_{\text{CF}}^{\text{expt.}}/\sigma_{\text{fus.}}^{\text{calc.}})$ and F_{ICF} [1]. As such, experimental measures of F_{ICF} are thought to provide an indirect measure of fusion suppression that is model independent.

When trying to understand the role of breakup in the observed suppressions of complete fusion, it has been conjectured that σ_{ICF} (and thus F_{ICF}) is entirely due to breakup of the weakly bound nucleus followed by capture of one of the fragments. However, it is very difficult to separate breakup followed by capture of one of the fragments from a transfer process forming the same nucleus. If transfer comprises a large fraction of σ_{ICF} , F_{ICF} cannot be attributed solely to breakup. Further, $\sigma_{\text{ICF}} + \sigma_{\text{CF}}$ can no longer be interpreted as the total fusion cross-section. In the case of ${}^7\text{Li} + {}^{165}\text{Ho}$, exclusive measurements of γ -rays and charged fragments favour the interpretation that σ_{ICF} is predominantly due to breakup [28]. While the interpretation of σ_{ICF} is ambiguous experimentally, it is clear within a classical model. By using PLATYPUS, the contribution of breakup to F_{ICF} can be determined.

PLATYPUS is designed to provide predictions of σ_{CF} and σ_{ICF} at energies above the barrier, through the use of the experimentally determined breakup functions, applied at above-barrier energies. In PLATYPUS, ICF is assumed to occur when one of the breakup fragments passes inside the barrier radius, while CF occurs when either the unbroken projectile or both breakup fragments pass the barrier radius. Calculations were performed using the near-target breakup functions determined from the least-squares fit to the below-barrier experimental breakup data, which have parameters as shown in Table I. Nuclear potentials were calculated using the São Paulo potential [29]. Calculations were performed for partial waves up to $100\hbar$, with 200000 breakup events simulated in total. The yield of near-target transfer-triggered breakup was attributed exclusively to breakup of the 2^+ resonance in ${}^8\text{Be}$, and thus the modelled excitation energies and lifetimes of the ${}^8\text{Be}$ projectile were those of the 2^+ state, as shown in Fig. 4. Near-target breakup of ${}^8\text{Be}$, in addition to arising from the 2^+ state, should have some contribution from the high excitation energy tail of the 0^+ state. Test calculations show that this contribution should be expected to *decrease* the overall F_{ICF} arising from near-target transfer-triggered breakup. This is because the average excitation energy of the high-energy tail of the 0^+ state is lower than that of the 2^+ state, as can be seen in Fig. 4. Hence the average lifetime is longer, and a smaller fraction of near-target breakup will occur prior to reaching the fusion barrier. Calculations of F_{ICF} were made at energies in $0.05V_B$ steps from $1.05 - 1.30V_B$, consistent with previous work [12]. Over the energy range of $1.05 - 1.30V_B$, F_{ICF} is energy dependent, and varies by a factor of two for each reaction, from $F_{\text{ICF}} = 0.16$ at $1.05V_B$ to 0.08 at $1.30V_B$ on average. The results from each energy step have been averaged to give a F_{ICF} value for each system, to compare to previous work, and to experimental measures.

The resulting σ_{CF} and σ_{ICF} are presented as F_{ICF} shown by the filled circles (blue) in Fig. 9. In contrast to expectations from the empirical prediction of Ref. [11], these new predictions show no significant dependence on target Z in the range studied in this work, and have a mean value of 0.11 ± 0.02 , which is indicated by the solid line Fig. 9. For comparison, the F_{ICF} predictions from Ref. [12] are shown by open circles. While several changes were made to the determination of coincidence efficiencies and extraction of breakup probabilities, the total change in the breakup functions used as input for calculations of above-barrier F_{ICF} was relatively modest, as already discussed. Therefore, the changes to PLATYPUS to model breakup of ${}^8\text{Be}$ through the 2^+ resonance are the major drivers towards the observed reduction of F_{ICF} by a factor of 2-3 relative to Ref. [12].

Experimentally, complete fusion suppression has been deduced, independently of σ_{ICF} , through comparison with reactions forming the same compound nucleus involving only well bound nuclei [2, 6]. Within the classical dynamical model followed in PLATYPUS, F_{ICF} and

complete fusion suppression are directly related, excepting some impact parameters outside the grazing trajectory that can only contribute to σ_{ICF} and not to σ_{CF} . To demonstrate that such trajectories do not make a significant contribution to σ_{ICF} , we performed calculations with PLATYPUS switching off breakup. The resulting fusion cross-section $\sigma_{fus}^{No\ BU}$ is compared with $\sigma_{CF}^{with\ BU}$ obtained with PLATYPUS. The quantity $(1 - \sigma_{CF}^{with\ BU} / \sigma_{fus}^{No\ BU})$, shown by purple triangles in Fig. 9, is very close to F_{ICF} . This demonstrates that contributions to σ_{ICF} from trajectories outside the grazing trajectory is small.

To understand the specific role of lifetime in F_{ICF} predictions, the lifetime of the 2^+ state was changed to be a factor of ten smaller. The results are shown by the blue pentagons in Fig. 9, and are typically a factor of two larger than previously (blue circles). This result makes the importance of explicit handling of lifetimes very clear. Indeed, the experimentally measured $\theta_{12}-\beta$ distributions compared to PLATYPUS simulations, shown in Fig. 5, already indicates that at below-barrier energies, the explicit inclusion of lifetimes change the breakup observables.

Experimental measurements of F_{ICF} (which include any contributions from transfer) are shown in Fig. 9 as solid squares for $^9\text{Be} + ^{208}\text{Pb}$ [2] and ^{144}Sm [7]. For F_{ICF} measurements to be made, both CF and ICF cross-sections must be measured. However, as both CF and ICF cross-sections are unavailable, fusion suppression factors $1 - \sigma_{CF}^{expt.} / \sigma_{fus}^{calc.}$ are shown for $^9\text{Be} + ^{209}\text{Bi}$ [4] and ^{186}W [10] as diamonds in Fig. 9. As both F_{ICF} and the fusion suppression factor are available for $^9\text{Be} + ^{208}\text{Pb}$ [2], both are shown, demonstrating the agreement between both measures in this system. The measured F_{ICF} and fusion suppressions for $^9\text{Be} + ^{209}\text{Bi}$ and ^{208}Pb are a factor of three times larger than the predicted contribution from neutron-transfer triggered breakup, and the experimental fusion suppression determined for $^9\text{Be} + ^{186}\text{W}$ is a factor of four times larger. The F_{ICF} determined for $^9\text{Be} + ^{144}\text{Sm}$ is consistent with the prediction. However, the measured ICF cross section in this experiment represents a lower limit, as cross-sections for ^{146}Gd and ^{148}Gd were not included [7]. Further, as indicated in Fig. 9, even with lifetimes that are a factor of ten smaller than those estimated from the width of the 2^+ resonance in ^8Be , the predicted F_{ICF} cannot be reconciled with experiment.

VII. CONCLUSIONS

Explicit inclusion of excitation energies and lifetimes of unbound resonances are crucial to model breakup. In the absence of a quantum mechanical model of transfer-triggered breakup, they have been included by modifying the classical dynamical code PLATYPUS. The new calculations show improved agreement with the measured energy and angular correlations of the breakup frag-

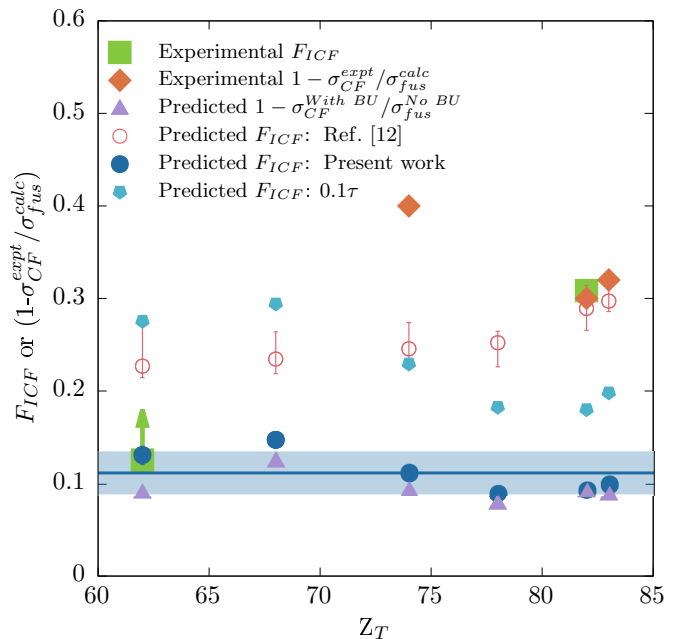


FIG. 9. (Colour online) Experimental values of F_{ICF} [4, 7] (filled squares), and $1 - \sigma_{CF}^{expt.} / \sigma_{fus}^{calc.}$ [2, 10] (filled diamonds), shown as a function of target Z . Predictions of F_{ICF} (filled circles) and complete fusion suppression (filled triangles) using the new breakup functions and the modified version of platypus. Error bars (determined from the uncertainty in the least-squares fit) are smaller than the points. The F_{ICF} and complete fusion suppression predictions show no clear trend with Z . The F_{ICF} prediction has a mean value of 0.11 ± 0.02 shown as the solid line, and the shaded bar indicates $\pm 1\sigma$. $1 - \sigma_{CF}^{With\ BU} / \sigma_{fus}^{No\ BU}$ has a mean value of 0.09 ± 0.02 . F_{ICF} predictions made using the lifetime of the 2^+ state ten times smaller than expected are shown with pentagons. F_{ICF} predictions from Ref. [12] are shown with open circles.

ments. These correlations show sensitivity even to the sub-zeptosecond lifetimes of the 2^+ state of ^8Be formed following n-transfer from ^9Be . Above the barrier, the inclusion of these lifetimes significantly reduces predicted above-barrier suppression of complete fusion. This occurs because a larger fraction of nuclei remain intact until reaching the barrier. As a result, predicted complete fusion cross-sections are not suppressed to the extent expected from earlier calculations that do not explicitly include lifetimes. This result is expected to apply to weakly-bound nuclei in general.

To make quantitative predictions of complete fusion suppression at above-barrier energies, breakup probabilities extracted from the experiments were used as input to the modified version of PLATYPUS that explicitly includes lifetime effects. This results in incomplete fusion to total fusion fractions F_{ICF} of $\sim 11\%$ at above-barrier energies. The related complete fusion suppression of $\sim 9\%$ is much less than the experimentally measured F_{ICF} and complete fusion suppressions of $30 - 40\%$ [2, 4, 10]

Three key conclusions are drawn from these results:

(1) As the calculated F_{ICF} is much less than measured, the cross-sections that are attributed experimentally to ICF may include a significant contribution from transfer directly producing the same heavy nucleus. This needs to be investigated in more detail.

(2) If σ_{ICF} contains contributions from both ICF and transfer, defining an empirical complete fusion suppression F_{ICF} in terms of σ_{ICF} is problematic.

(3) The observed reduction of complete fusion at above-barrier energies has been measured independently of σ_{ICF} in several reactions through direct comparison with reactions of well bound nuclei [2, 6]. Since breakup cannot explain this, then other processes must contribute. Experimental values of F_{ICF} and $1 - \sigma_{CF}^{expt.} / \sigma_{fus}^{calc.}$ have been found to be similar [2], thus it is reasonable to suspect that the two quantities are linked. Therefore, if transfer is shown to make a large contribution to products previously attributed to ICF, then a mechanism by which transfer may suppress complete fusion needs to be considered. In a classical picture, if transfer removes energy from the relative motion, it will reduce fusion. However in a coupled-channels approach, it is not clear whether above-barrier fusion can be suppressed by transfer. These questions require further investigation.

ACKNOWLEDGMENTS

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Appendix A: Removal of cross-talk events

In the previous work, spurious coincident events resulting from charge-sharing across adjacent pixels resulting from cross-talk or particles crossing the inter-strip partition, were removed by rejecting *any* event in adjacent pixels. With greater experience in analysis of such data, it was realised that these events can be rejected by their unphysical relative energy (E_{rel}), with respect to their opening angle (θ_{12}). In this analysis, spurious events were removed by applying cuts in the E_{rel} - θ_{12} spectra. This alternate method for extracting breakup events resulted in an approximately four times larger yield of the ground-state ^8Be events, as the vast majority of genuine ^8Be ground-state breakup events result in signals in adjacent pixels. These lost events would otherwise have had to be restored by a larger efficiency correction.

Appendix B: Normalisation

The expected yield of Rutherford scattering $N_{Ruth}(\theta_{Ruth})$ may be determined from the yield of Rutherford scattered particles $N_{Ruth}(\theta_{norm})$ in the $\theta_{norm} = 124^\circ$ to 127° elastic normalisation bin,

$$N_{Ruth}(\theta_{Ruth}) = N_{Ruth}(\theta_{norm}) \left(\frac{d\sigma}{d\Omega}(\theta_{bin}) \right) \left(\frac{d\Omega_{bin}}{d\Omega_{norm}} \right), \quad (B1)$$

where $\frac{d\sigma}{d\Omega}(\theta_x)$ and $d\Omega(\theta_x)$ are the differential cross-sections and solid angles respectively. As the efficiency corrected breakup yield corresponds to the number of coincidence breakup events over all azimuthal angles, the calculated Rutherford yield must be for this same angular range. In Ref. [12] the Rutherford yield was calculated within the coverage of BALiN. This leads to a downwards correction in the present study by a factor of ~ 0.75 equal to the fractional coverage of the BALiN array in azimuthal angle.

As θ_{norm} is at a relatively backwards angle, the elastic yield is purely Rutherford only for deep sub-barrier measurements. Where measurements were made near to the barrier, the expected $N_{Ruth}(\theta_{norm})$ was calculated from the elastic yield, $N_{elas}(\theta_{norm})$, by taking the ratio of the elastic and Rutherford cross sections determined from optical model fits of existing elastic scattering data [30–33], such that

$$N_{Ruth}(\theta_{norm}) = N_{elas}(\theta_{norm}) \left(\frac{d\sigma_{elastic}/d\Omega}{d\sigma_{Rutherford}/d\Omega} \right) (\theta_{norm}). \quad (B2)$$

The correction was largest for $^9\text{Be} + ^{208}\text{Pb}$ and ^{209}Bi at $E_{beam} = 37$ MeV, where $\frac{d\sigma_{elastic}/d\Omega}{d\sigma_{Rutherford}/d\Omega}(\theta_{norm}) = 0.89$. The solid angle coverage of the normalisation bin $d\Omega_{norm}$ can be determined from the solid angle coverage of BALiN by comparing the yields in normalisation bin and in each θ bin of BALiN at a beam energy E_{cal} where the elastic yields do not significantly deviate from Rutherford scattering for all angles. In that case, we can write

$$d\Omega_{norm} = \frac{N_{norm}(\theta_{norm}, E_{cal})}{N_{Ruth}(\theta_{bin}, E_{cal})} \frac{\frac{d\sigma}{d\Omega}_{Ruth}(\theta_{bin}, E_{cal})}{\frac{d\sigma}{d\Omega}_{Ruth}(\theta_{norm}, E_{cal})} d\Omega_{bin}, \quad (B3)$$

where $d\Omega_{bin}$ is the solid angle coverage for each θ bin in BALiN.

Appendix C: Efficiency Determination

Using the notion of θ_{sBe} , the geometric coincidence efficiency was given by the ratio of simulated breakup events that would have landed in BALiN at each θ_{sBe} and θ_{12} , (taking into account the azimuthal coverage of BALiN) to the simulated events distributed over all azimuthal angles. The simulated events were subject to the

same detector conditions as the experimental data. As an example, the geometric coincidence efficiency matrix determined for ${}^9\text{Be} + {}^{208}\text{Pb}$ at 34.0 MeV is shown in Fig. 10(c). This was determined from the ratio of the number of events within the acceptance of BALiN, Fig. 10(b), to the total number of events, Fig. 10(a), in each $(\theta_{\text{sBe}}, \theta_{12})$ bin. The experimentally determined $(\theta_{\text{sBe}}, \theta_{12})$ distribution for the same system is shown in Fig. 10(d). The geometric coincidence efficiency shows two triangular regions of high detector efficiency – at small $\theta_{12} \sim 10^\circ$ with $\theta_{\text{sBe}} \sim 135^\circ$ corresponding to the centre of the BALiN array, and at $\theta_{12} \sim 80^\circ$ at backward $\theta_{\text{sBe}} \sim 180^\circ$. The former is due to events with sufficiently small opening angle so that both fragments land on the same DSSD, while the latter is due to events that strike two different DSSDs. For values of θ_{sBe} where BALiN gives coverage, for some values of θ_{12} the efficiency is zero. A correction to account for this is made in the next stage in the determination of the efficiency.

To simulate the distribution of fragments, shown Fig. 10(a), needed for this second part of the efficiency correction, PLATYPUS calculations using the modifications discussed in Sec. IV were performed. Simulations of near-target (high E_{rel}) breakup events were performed using the excitation energy and excitation energy dependent mean life for ${}^8\text{Be } 2^+$ as discussed in Sec. IV. Q-value distributions were taken from the experimental results, and the energy of the ${}^8\text{Be}$ pseudo-projectile (E'_P) calculated by matching the distance of closest approach to that attained by the ${}^9\text{Be}$ beam with energy E_P , as PLATYPUS does not simulate transfer. In analogy to the optimum Q-value of [34], this matching energy is given by

$$E'_P = E_P \frac{m_T}{m'_T} \left(\frac{Z_P Z_T}{Z'_P Z'_T} \right), \quad (\text{C1})$$

where Z_T, m_T, Z_P, m_P and Z'_T, m'_T, Z'_P, m'_P is the charge and mass of the target and projectile before and after transfer, respectively. In this case, where only neutron transfer is occurring, the matching energy is very close to the experimental beam energy. In cases such as the breakup of ${}^7\text{Li}$, where proton transfer dominates, this factor becomes more important. The projectile-target and fragment-target potentials are Woods-Saxon parameterisations of São Paulo potentials [29], from [12]. This is used for all PLATYPUS simulations in this work. According to these simulations, events that have θ_{sBe} where BALiN gives coverage, but have θ_{12} where the efficiency is zero accounted for $\sim 7\%$ of all events simulated within the θ_{sBe} acceptance of the array. As such, this second step in efficiency correction represents a small (though θ_{sBe} dependant) model-dependent addition to a model-independent efficiency correction.

Appendix D: Comparison of efficiencies in Ref. [12] and the present work

The coincidence efficiencies determined in this work differ from those found in Ref. [12]: there, prompt efficiencies were given for two 15° bins in θ_{sBe} , $\epsilon_{121-136^\circ} = 0.25$ and $\epsilon_{136-151^\circ} = 0.42$, and the efficiencies were found to be nearly independent of E_{lab} . Here, the efficiencies are calculated in 5° bins in $(\theta_{12}, \theta_{\text{sBe}})$, and so are much more fine-grained. However, when averaged over the same range of θ_{sBe} , the efficiencies in this work are on average $\epsilon_{121-136^\circ} = 0.17$ and $\epsilon_{136-151^\circ} = 0.40$. As the efficiency corrections in this work take into account θ_{12} , the distribution of which changes with E_{lab} and Z , these averaged efficiencies are not independent of E_{lab} or Z .

These differences between Ref. [12] and the present work can be accounted by three factors: (i) In the previous analysis, efficiencies were calculated as a function only of θ_{sBe} . As seen in Fig. 10(c), for events with a $(\theta_{12}, \theta_{\text{sBe}})$ distribution as shown in Fig. 10(a), the efficiency varies strongly as a function of θ_{12} for fixed θ_{sBe} . Thus, efficiency correction only as a function of θ_{sBe} results in an average over-correction in the number of breakup pairs for each θ_{sBe} by a factor of ~ 1.1 for the systems studied in this work (depending on θ_{sBe} , target mass and beam energy), compared to the new two-dimensional efficiency correction performed here. (ii) The efficiencies further change as the early version of PLATYPUS used in Ref. [12] did not have a fully isotropic distribution of initial fragment directions: there was an over-abundance of events with similar scattering angles, $\theta_1 \sim \theta_2$, leading to an artificially high efficiency. PLATYPUS was corrected in late 2010 [35]. (iii) The modifications of PLATYPUS performed for this work resulted in a different angular distribution of fragments and so changed the model-dependent stage of the efficiency corrections.

Appendix E: Local Breakup Probabilities

Since interacting nuclei spend more time near the distance of closest approach, then casting the breakup probability as

$$\frac{dP}{dr} \propto e^{\mu r}, \quad (\text{E1})$$

in a dynamical model is inappropriate. To illustrate this, consider a classical Coulomb trajectory, where

$$\frac{dt}{dr} = \frac{r}{v \sqrt{(r - a_0(1 + \epsilon))(r - a_0(1 - \epsilon))}}, \quad (\text{E2})$$

and $a_0 = Z_p Z_t e^2 / \mu v^2$, $\epsilon = \sqrt{1 + (L/\eta)^2}$ and the Sommerfeld parameter $\eta = Z_p Z_t e^2 / v$, where μ is the reduced mass, and v the incident velocity. Then,

$$\frac{dP}{dt} = \frac{dP}{dr} \frac{dr}{dt} \propto e^{-\mu r} \frac{v \sqrt{(r - a_0(1 + \epsilon))(r - a_0(1 - \epsilon))}}{r}. \quad (\text{E3})$$

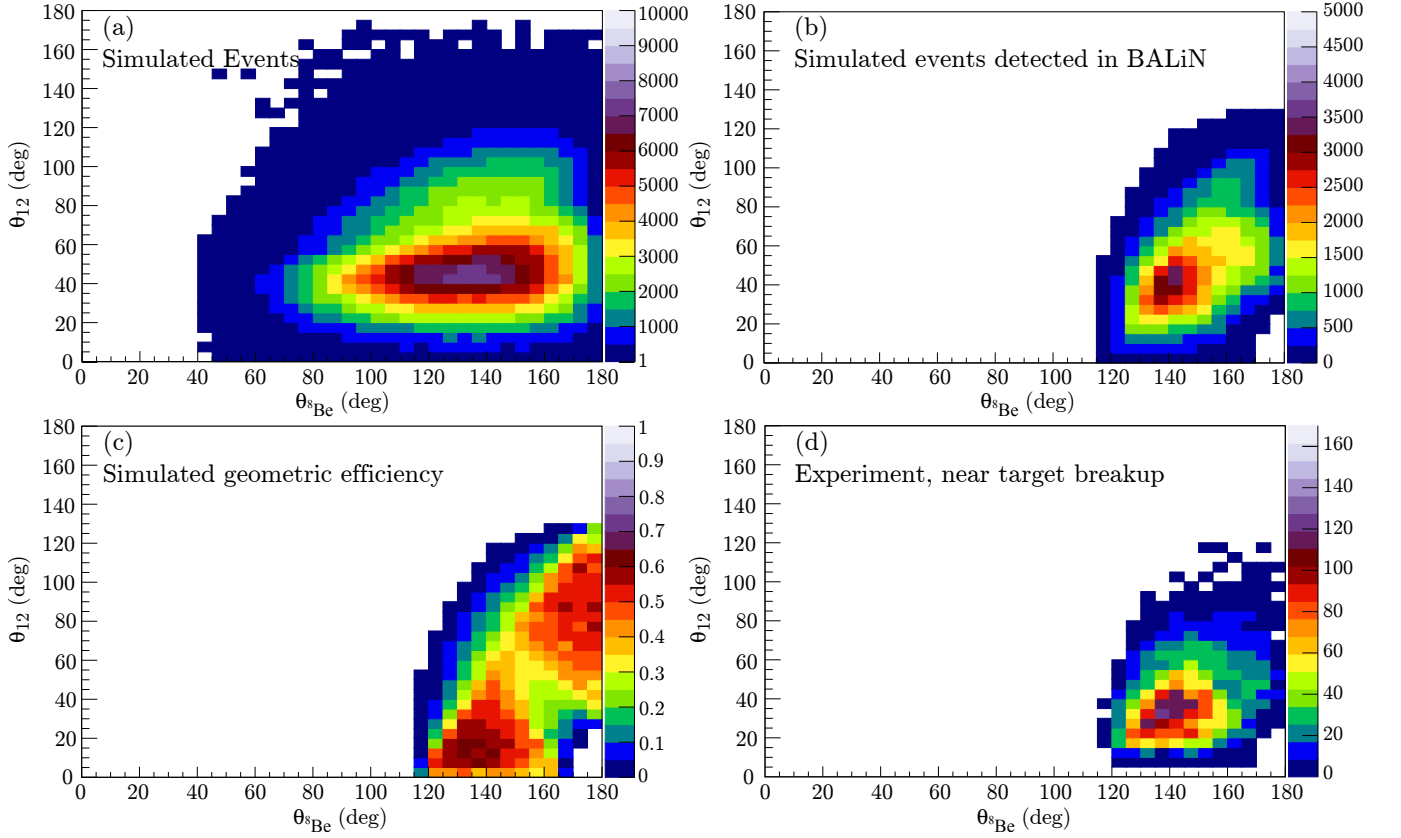


FIG. 10. (Colour online) Simulated and experimental near-target $\theta_{s\text{Be}} - \theta_{12}$ distributions for ${}^8\text{Be}_{2+} + {}^{208}\text{Pb} \rightarrow \alpha + \alpha + {}^{207}\text{Pb}$ at $E_{\text{Beam}} = 34$ MeV. (a) Total simulated distribution. (b) The same events filtered by the acceptance of the BALiN array. (c) The associated geometric coincidence efficiency of the BALiN array determined from the simulated events filtered by the acceptance of BALiN divided by the total simulated events in each $(\theta_{s\text{Be}}, \theta_{12})$ bin. (d) Experimental $\theta_{s\text{Be}} - \theta_{12}$ distribution for near-target breakup events [region (ii) of Fig. 1] showing the good correspondence between the filtered simulated data and the experiment

For a trajectory corresponding to scattering at 180° , $\epsilon = 1$ and the distance of closest approach, $R_0 = 2a_0$, this

results in $dP(R_{\min})/dt = 0$ at the distance of closest approach, which does not seem reasonable.

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